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Interim Topical Report

Supercritical CO_2 Plant Cost Assessment

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Abstract

This report presents interim results on cost projections for the supercritical CO_2 Brayton indirect power cycle as applied to GEN-IV advanced reactors.

Design features are reviewed which favor cost effectiveness, such as exploiting the compact nature of this cycle to allow factory fabrication of power conversion modules as large as 300 MWe rating, and their transport to the reactor site in as few as one to three pre-assembled packages.

A differential cost comparison procedure is adopted in which projections are made relative to authoritative published cost estimates for related reactor systems such as thermal spectrum HTGRs coupled to direct and indirect cycle helium Brayton power conversion units and to the conventional indirect Rankine steam cycle. It is preliminarily concluded that savings, conservatively on the order of 10%, may be achievable, with the dominant parameters being cycle thermodynamic efficiency and turbomachinery capital cost. Approaches to further cost analyses and reduction are identified.

Acknowledgements

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1 Introduction

1.1 Foreword

This topical report is the contractually required interim progress report on Task 2, which covers design, layout and cost assessment for a supercritical CO_2 Brayton power plant used as an indirect cycle coupled to GEN-IV reactors. The main focus of this report is on plant cost and cost of generated energy aspects. It recapitulates and updates the information in one of our recent reports which also deals with this topic, namely:

M. J. Driscoll, P. Hejzlar, **300 MWe Supercritical CO_2 Plant Layout and Design,** MIT-GFR-014, June 2004

1.2 Background

The use of S-CO_2 power cycles for advanced reactors is not a new topic, nor are their potential cost advantages.

In the late 1960's /early 1970's time frame Siemens evaluated both direct and indirect cycle CO_2 turbine cycles for fast reactors (S-2). They found that their CO_2 /CO_2 combination had an efficiency 2% lower than a CO_2 /Rankine unit, while a Na/CO_2 combination was 3% less efficient (e.g. 38% vs. 41%). However they conclude that "the CO_2 turbine must have an enormous cost advantage compared to steam turbines due to size, and compared to Helium turbines due to moderate temperatures". Sulzer engineers studied a He/CO_2 combination and concluded that "for future gas-cooled fast breeders and even for high temperature gas-cooled reactors CO_2 –indirect cycles could be advantageous by replacing steam cycles or even direct Helium cycles" (S-3).

Note that this prior work conceded an efficiency advantage to the Rankine cycle—which is at odds with our current intentions and findings. A principal difference is our use of enhanced recuperation (made possible by the development of compact heat exchangers): i.e. a ratio of recuperated to added heat of 2.5 vs. 0.98 to 1.7 in the Sulzer designs.

Finally, none of these earlier studies cited hard data on comparative costs in terms of $/kWe or mills/kWhr. This lack of quantitative information motivated initiation of the present task, on which this report is an installment.

2 Plant Configuration

2.1 Chapter Introduction

Certain aspects of power conversion unit (PCU) design and layout are central to cost forecasting. Hence this subject is reviewed briefly in this preliminary chapter. The central theme is exploitation of modularity: factory fabrication of power plant modules followed by rail and/or road transport of intact sub-units to the site. This is in strong contrast to how Rankine cycle units are deployed. As will be seen, this up-front requirement limits S-CO_2 PCU rating to about 300 MWe. Hence a 1200 MWe reactor would have four loops, each complete with their own electric generators. A steam plant, on the other hand, would have a single 1200 MWe turbine-generator-condenser train constructed from components on site. Another practical reason for the specification of a 300 MWe PCU is that current state of the art design, manufacturing and operating experience for similar turbomachinery (supercritical steam and combustion gas turbines) is for components of comparable physical size. Finally a 300 MWe PCU allows one to deploy 300, 600, 900, 1200 MWe reactors as demand dictates (see Figure 2.1).

While we will proceed under this modularity-imposed size constraint, it should be noted that no technical constraints on S-CO_2, turbomachinery have yet been identified which would prohibit design of a single-loop 1200 MWe unit if this should ever prove desirable, especially if a double flow arrangement were adopted (plus, if necessary, using separate turbines or electric motors to drive the compressors). One would have to first confirm that casing and blade stresses are tolerable.

Another caveat is that we have not adopted the extreme modularization approach created for the MIT Modular Pebble Bed Reactor, in which a larger number (21) of much smaller modules (8' x 12' x 60', ≤ 200,000 lb) are specified to permit transport to site of the entire balance-of-plant by a heavy-lift tractor/trailer truck. (K-1) This approach could however, be used for other than our PCUs.

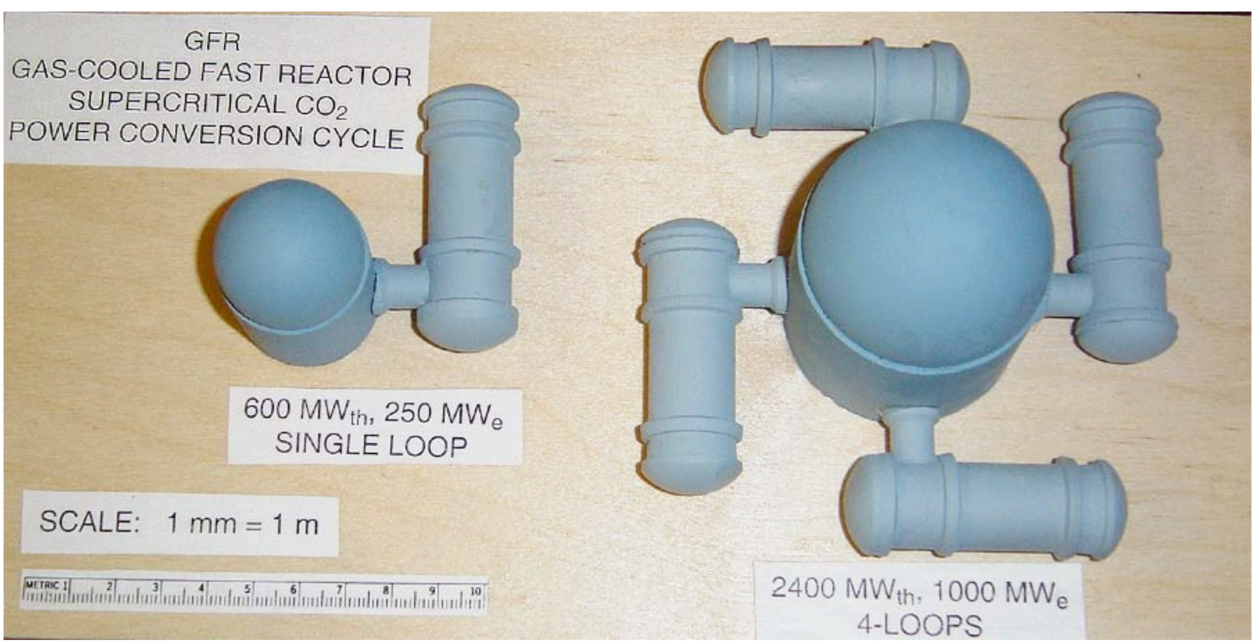


Fig. 2.1 Model of Single and Four-Loop Reactor Arrangements

2.2 PCU Concepts

In this section we collect for reference purposes, three layouts originally examined in earlier monthly, quarterly and topical reports:

A single vessel integral concept similar to that chosen for the (vertical) GA-Russian GT-MFR, except that ours is horizontal: See Figs. 2.2 and 2.3
A two-vessel approach in which the turbomachinery nacelle is separate from the heat exchanger (recuperator plus precooler) vessel: See Figs. 2.4 and 2.5
A four-vessel "tripod" arrangement in which two parallel recuperator vessels are employed, with a single separate precooler: See Figs. 2.6 and 2.7

After considering the pro's and con's of each, we have downselected to the two-vessel layout, primarily on the basis that much better access is provided during both operation and (especially) maintenance for monitoring, inspection and rapid repair of turbomachinery and valves, and for periodic cleaning of the precooler waterside. Its main drawback is the five high-pressure ducts connecting the heat exchanger and turbomachinery vessels. A priority next step must be to carry out a stress analysis of this arrangement. It may prove necessary to use □ or S-shaped ducts to help accommodate steady state and transient thermal stresses, which will increase parasitic pressure drops and thus penalize efficiency. Because a small amount of CO_2 losses are tolerable compared to helium—and likely to be at a lower rate because of CO_2's higher molecular mass—it may be possible to use bolted flanges as opposed to field welds to connect the two vessels. S- CO_2's lower operating temperature (550-700°C) vs. He (850-1000°C) will also lessen thermal stress concerns.

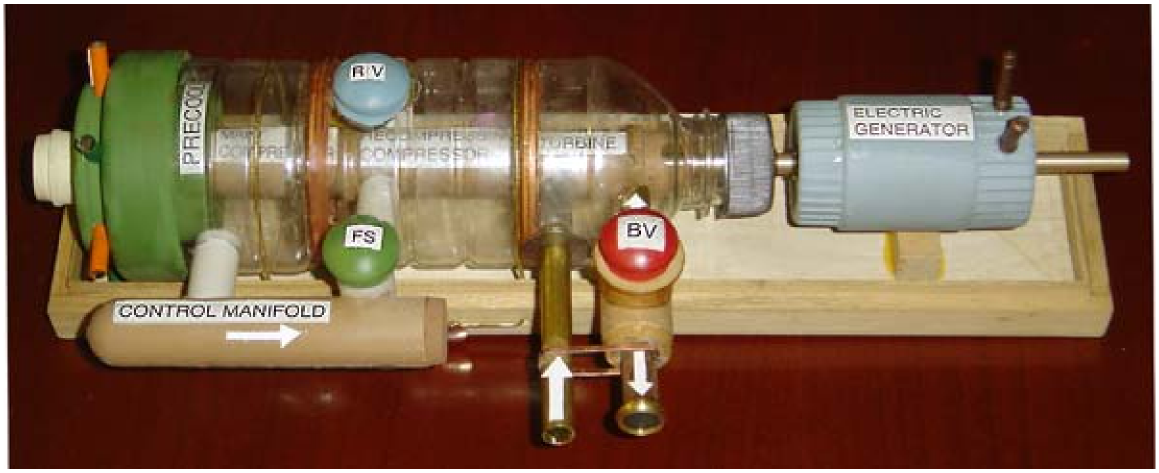


Fig. 2.2 Photograph of Single-Vessel PCU Model
(Transparent Vessel, Annular Recuperator Cluster Removed)

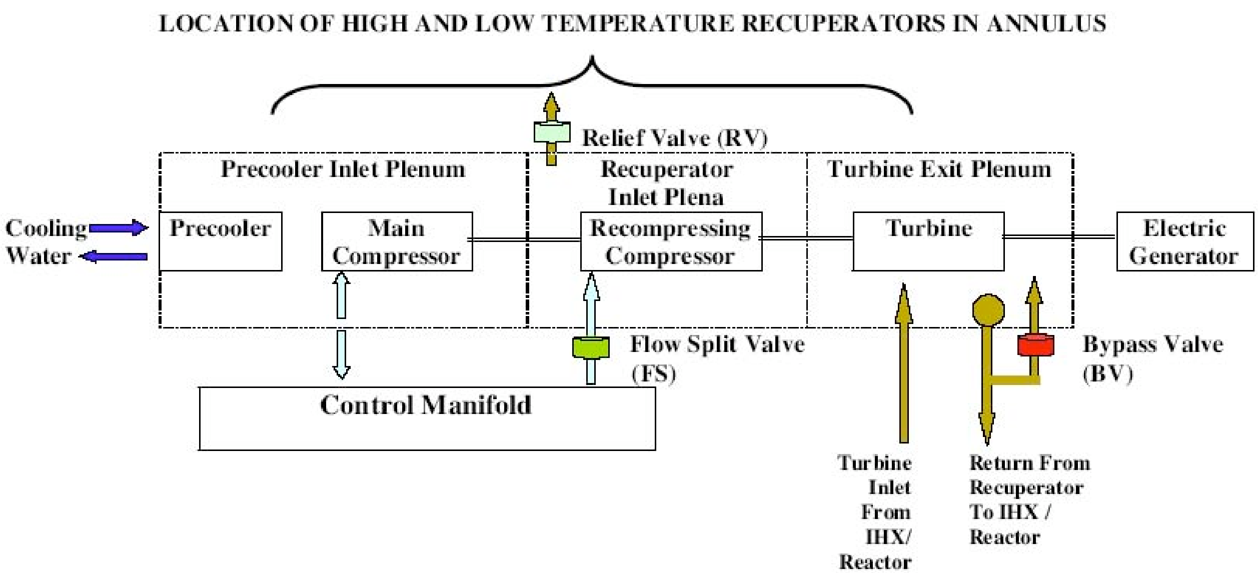


Fig. 2.3 Key to Layout of S-CO_2 PCU Model

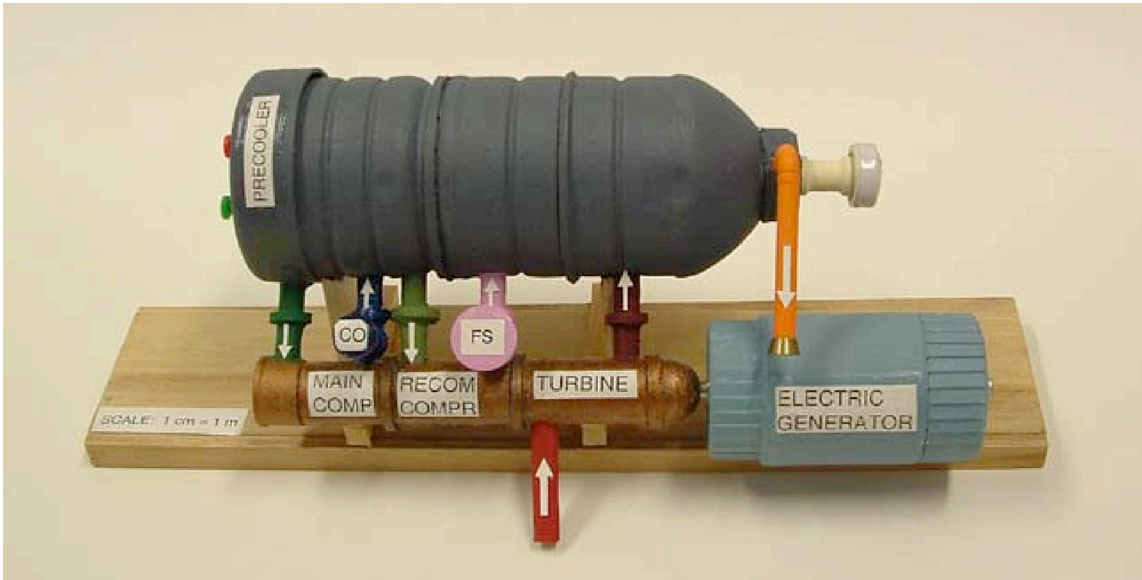


Fig. 2.4 Model of Two-Vessel Plant Layout

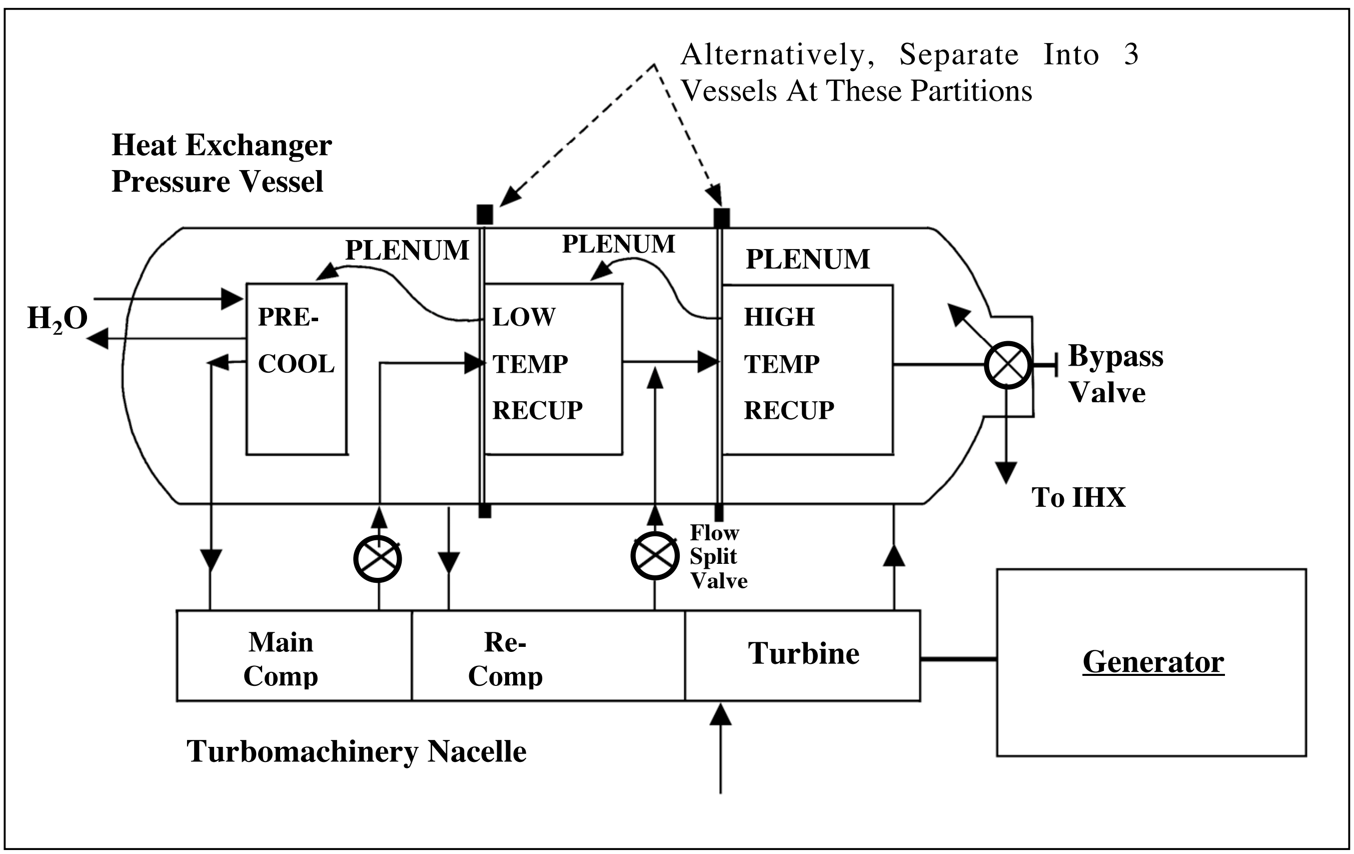


Fig. 2.5 Unbundled Two to Four Vessel Power Cycle Layout

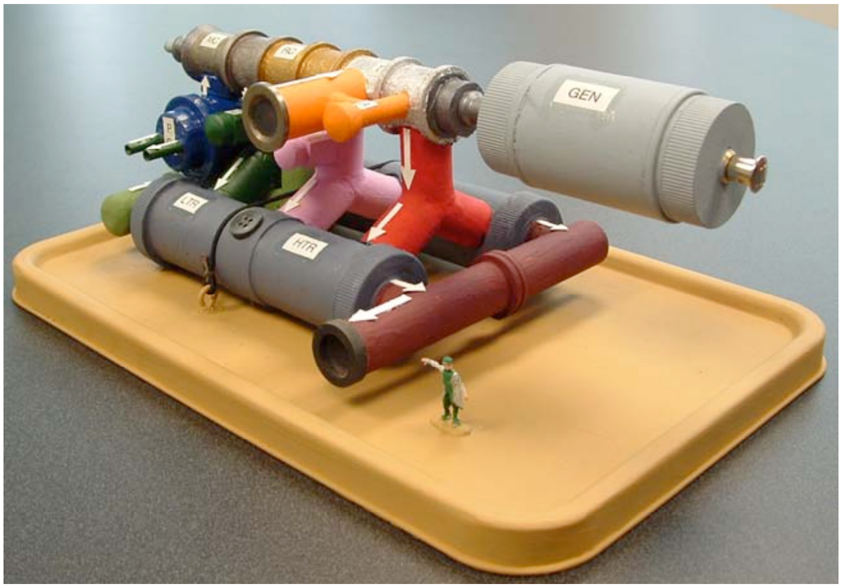
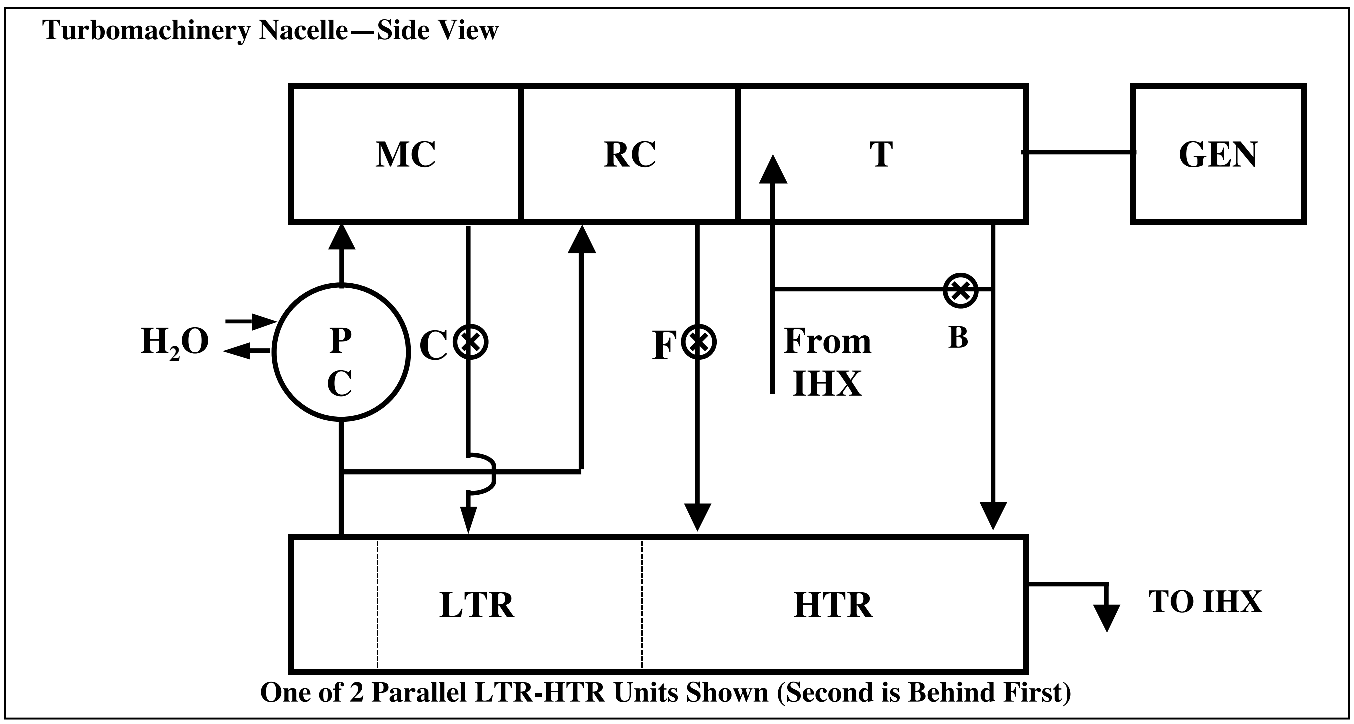


Fig. 2.6 Picture of Model of "Tripod" Power Conversion Cycle Layout



Key:				
	MC	= Main Compressor	LTR	= Low Temperature Recuperator
	RC	= Recompressing Compressor	HTR	= High Temperature Recuperator
	T	= Turbine	C	= MC Control Valve
	GEN	= Electric Generator	F	= Flow Split Valve RC/MC
	PC	= Precooler	B	= Turbine Bypass

Fig 2.7 Component Layout for "Tripod" Power Conversion Cycle

2.3 Transportability

A brief survey of transport industry capabilities was carried out to help define the upper limit on modularity and thus PCU rating. In general, most sites should be accessible using special purpose rail cars (Schnabel-type) and a similar road-trailer configuration, as shown in Figs. 2.8 and 2.9. Roughly, loads of 350 tons up to 5 m diameter and 20 m long can be moved in this manner.

In the present work we do not consider the issue of modularity and transportability as it relates to reactor primary circuit design and construction. However it is of interest to note that the S-CO_2 PCU recuperators have a combined thermal duty about 2.5 times that of the intermediate heat exchanger linking the primary system to the power cycle. Hence IHX transportation, possibly with an integral blower-check valve assembly, would readily be feasible.

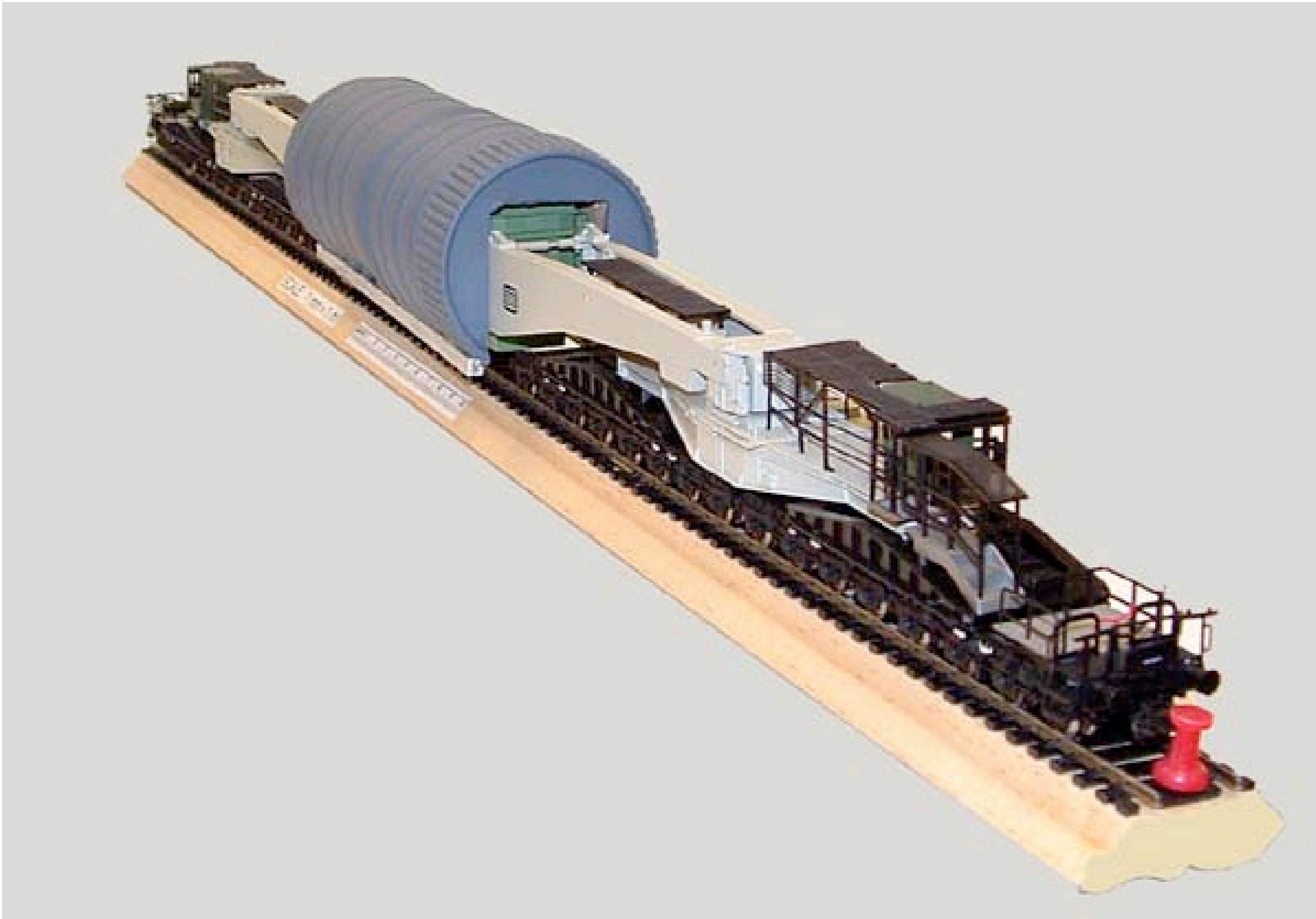


Fig. 2.8 Schnabel Railcar Bearing a PCU Vessel

Fig. 2.9 Steam Generator Transported Using Heavy-Duty Road Trailers (Siemens)

3 Economic Assessment

3.1 Chapter Introduction

In this chapter a quantitative analysis is made of the potential for cost savings if the supercritical CO_2 cycle is employed as an indirect power conversion unit for GEN-IV reactors. We apply a differential approach, starting with authoritative, consistently-generated industrial assessments such as Ref (G-1). This is in contrast to an independent start-from-scratch approach in which all of the entries in the DOE Energy Economic Data Base (EEDB) Code of Accounts for a reactor are independently estimated. This avoids a myriad of confounding factors which add greatly to the uncertainty in the bottom-line total. References (M-1) and (C-1) testify to what happens when proponents develop stand-alone economic estimates for new nuclear plants, even for evolutionary LWRs: the range of \$/kWe values these studies are led to consider (≈±20%) by working with estimates published by others is as large or larger than is likely to be realized by introducing a technical innovation such as the S-CO_2 power cycle. Another source of uncertainty is the difference between a first-of-a-kind (FOAK) unit and N-th unit mature costs; here we focus on the latter. In Ref (G-1) a FOAK He/He indirect cycle MHTGR/GT is estimated to have a busbar cost some 37% higher than a mature "target" unit: all the more reason to beware of indiscriminate borrowing from the literature.

3.2 Development of a Framework for Cost Comparisons

3.2.1 Derivation

A principal criterion for selection among advanced reactor designs is their projected cost of electricity generation. Absolute comparisons of this type are fraught with considerable uncertainty, even for evolutionary LWRs. However, one can gain useful insight from simple differential comparisons.

The busbar cost of electricity, in mills /kWhre, is comprised of three major components, corresponding to contributions by capital cost, those for operation and maintenance, and that for fuel. One has:

Capital

$$e_C = \frac{\phi I}{8766\ Q \eta L} \qquad (3\text{-}1)$$

where

ϕ =	Fixed Charge Rate, % per yr
I =	Capital cost, including escalation and interest during construction, \$
η =	Thermodynamic efficiency, kWe/kW_{th}
L =	Average capacity factor, fraction of full power
Q =	Plant rating, kW_{th}
Note that since $Q\eta$ = K, kWe, an alternative formulation in terms of the oft-cited (I/K), \$/kWe, is also possible	

O&M

$$e_{om} = \frac{100\ \square}{8766\ \ Q \square L} \qquad (3\text{-}2)$$

where $\square$ = lifetime levelized cost of O&M, \$/yr

Fuel

$$e_f = \frac{100}{24}\ \frac{F}{B_O \square L} \qquad (3\text{-}3)$$

where F = lifetime levelized cost of fuel, \$/kg
B_O =burnup if L = 1.0, MWd_{th}/kg (Note that this model assumes fixed refueling dates)
and the total busbar cost is:

$$e_b = e_c + e_{om} + e_f \qquad (3\text{-}4)$$

For small changes about a base case at constant Q, F and B_O, and assuming independence among the variables, it is not difficult to show that:

$$\begin{aligned} \frac{\square e_b}{e_b} &= f_c \square \frac{\square I}{I} \square \frac{\square \square}{\square} \square \frac{\square L}{L} \square \\ &+ \ f_{om} \square \frac{\square \square}{\square} \square \frac{\square \square}{\square} \square \frac{\square L}{L} \square \\ &+ \ f_f \square \square \frac{\square \square}{\square} \square \frac{\square L}{L} \square \end{aligned} \qquad (3\text{-}5)$$

where f_c, f_{om}, f_f are the fractions of busbar costs attributable to capital, O&M and fuel $\left(e_c/e_b,\ e_{om}/e_b,\ e_f/e_b\right)$, respectively, for the reference case.

This simplifies to:

$$\frac{\square e_b}{e_b} = f_c \square \frac{\square I}{I} \square + f_{om} \square \frac{\square \square}{\square} \square \square \frac{\square \square}{\square} \square \frac{\square L}{L} \qquad (3\text{-}6)$$

3.2.2 Application of Method

Reference (G-1) is a particularly useful source of relevant data for present purposes. It compares indirect cycle HTGRs coupled to Rankine and (helium) Brayton power conversion systems. Table 3.1 is excerpted; it applies to "target" (i.e. mature) versions of each.

Applying Eq. (3-6), one has, using the steam cycle (SC) unit as the reference plant, and the gas turbine indirect cycle (GT/IC) as the challenger:

$$\frac{\Delta e_b}{e_b} = 0.63\ (0.22)\ - 0.22\ (0.10)\ - 0.16 - 0 \qquad (3\text{-}7)$$
$$= -0.043$$

The reference also provides e_b directly, from which (including decommissioning costs):

$$\frac{\Delta e_b}{e_b} = \frac{-2}{51} = -0.039 \qquad (3\text{-}8)$$

which is in good agreement considering the approximate nature of our treatment.

Table 3.1: MHTGR Busbar Generating Costs ('92$) Target Plants –2016 Startup

Excerpted from Ref (G-1)

	STEAM CYCLE	INDIRECT CYCLE	DIRECT CYCLE
REACTOR THERMAL POWER (MWt)	4x450	4x450	4x450
NET EFFICIENCY (%)	38.5%	44.8%	48.3%
NET ELECTRIC RATING (MWe)	693	806	869
CAPACITY FACTOR	84%	84%	84%
TOTAL CAPITAL COST (M$)	1,658	2,016	1 704
UNIT CAPITAL COST ($/kWe)	2.393	2,501	1,961
FIXED CHARGE RATE	9.49%	9.49%	9.49%
LEVELIZED CAPITAL COST (M$/YR)	157	191	162
FIXED O&M COST (M$/YR)	34.6	31.1	27.6
VARIABLE O&M COST (mills/kWh)	0.2	0.2	0.2
CONTROL ROD & REFLECTOR REPLACE (M$/YR)	4.8	4.8	4.8
ANNUAL O&M COST (M$/YR)	40.6	37.0	33.5
FUEL COST ($/MBTU)	1.26	1.27	1.28
LEVEL FUEL CYCLE COST (M$/YR)	56.7	57.6	58.0
DECOMMISSIONING COST (M$)	194	199	199
LEVEL DECOMMISSIONING (M$/YR)	5.2	5.4	5.4
REVENUE REQUIREMENT (M$/YR)	260	291	259
BUSBAR COST (mills/kWh)			
CAPITAL	30.9	32.2	25.3
O&M	8.0	6.2	5.2
FUEL	11.1	9.7	9.1
DECOMM	1.0	0.9	0.8
TOTAL	51.0	49.0	40.4
BUSBAR COST RELATIVE TO TARGET MHTGR—SC	1.00	0.96	0.79

3.2.3 Discussion of Benchmark Comparison

Some points worthy of note on the preceding cost comparison are as follows:

1. The GT/IC unit has a <u>higher</u> capital cost than the SC version. This may well reflect the fact that steam plants are advantaged by more than a century of learning-curve savings, whereas helium turbine Brayton cycles are novel, with only several small fossil-fired precursors.

2. No credit for improved GT capacity factor is assumed—again possibly a consequence of the much larger steam cycle experience base. A significant O&M benefit is credited, however, which is consistent with staff reductions needed for balance-of-plant operations and maintenance.

3. The largest savings follows directly from increased cycle thermodynamic efficiency, which helps justify the virtual obsession with this metric in most power cycle studies.

4. The small net GT/IC advantage of 4% of busbar cost makes evident why GCRA favored the direct cycle (GT/DC). Applying our simple prescriptions to the values in the table for that option gives $\frac{\Delta e_b}{e_b} = -0.28$, in excellent agreement with the tabulated value of –0.26.

3.3 Implications for S-CO_2 Cycle In Indirect Gas-to-Gas Applications

The supercritical CO_2 cycle, if operated at a turbine inlet temperature of 700°C, should be able to provide a net thermodynamic efficiency of about 44%, allowing for around 4% reduction because of indirect cycle service. Thus $\left(\frac{\Delta \eta}{\eta}\right) = 0.14$. O&M savings should fall between the MHTGR IC and DC values: hence $\Delta\phi/\phi \approx -0.15$. Capital costs should be about 5% less than that of the helium indirect cycle (the GT plant is about 20% of total costs and the S-CO_2 version should be about 20% cheaper than the He version), so that $\frac{\Delta I}{I} = 0.155$ (hence remaining more expensive).

The above values predict a busbar cost for the indirect S-CO_2 reactor relative to the Rankine steam cycle of $\frac{\Delta e_b}{e_b} = -0.075$, compared to the GCRA estimate of –0.04 for an indirect He Brayton plant.

This would be a useful improvement, if further analysis supports these rough back-of-the envelope estimates.

There are several reasons for regarding the above estimates as being conservative:

a. The helium Brayton core outlet temperature is about 850°C (based on recent GA GT-MHR design specifications); this can be lowered to ≈750°C to power an S-CO_2 indirect cycle having a 700°C turbine inlet temperature, which should translate into cost savings for the primary coolant system and IHX.
b. Alternatively, it is not out of the question to consider operating at 800°C, in which case the efficiency increase of about 2.5% (vs. @ 700°C) would lead to a further savings in $\Delta e_b/e_b$ of – 0.057.
c. We have not taken credit for potential auxiliary system capital cost and O&M savings resulting from the fact that CO_2 is some two orders of magnitude cheaper than He on a per unit mass basis, leading to much smaller makeup costs, and cheaper, less leak-proof system designs. CO_2 can also be readily stored as a liquid at high density and relatively low pressure.

Other potential savings are discussed in Chapter 4.

3.2 Applicability to Other GEN-IV Reactors

As indicated earlier, high thermodynamic efficiency is a major driver favoring consideration of the S-CO_2 cycle. Using Ref (D-3) we estimate in Table 3.2 what should be achievable for the full roster of GEN-IV reactor concepts. Obviously one would probably not give serious consideration to S-CO_2 use for a supercritical steam cooled reactor (although the low, ≈150°C, ΔT across the reactor might ameliorate core flow stability problems in this system). The other five concepts are all candidates for its use. Also note that we do not include in this table the direct cycle GFR, which may well be its most attractive application: see Ref(D-3) for further information.

The application of the S-CO_2 cycle to lead alloy cooled fast reactors has been evaluated in the recent past at MIT (D-4) and is the subject of ongoing work at ANL (S-1). The ANL design has a core outlet temperature of 588°C, a turbine inlet temperature of 564°C and a cycle efficiency of 45%. For a similar LMR, MIT (D-3) estimated a Rankine cycle efficiency of 42.8% for an HP turbine inlet temperature of 560°C. In subsequent analyses the S-CO_2 cycle is estimated to have an efficiency of 43.8%. (After deduction of all house loads, these values are reduced by about 2%). Thus, referring to Eq. (3-6), this by itself would reduce busbar costs by about 2.3%.

Table 3.2 Applicability of S-CO_2 Indirect Cycle to GEN-IV Reactors

Concept	Reactor Outlet T [1]	S-CO_2 Turbine Inlet T [3]	Est. S-CO_2 Cycle Thermal Efficiency [4]
GFR	850°C (He)	800°C	53
LFR	550-800°C	530-780°C	43-52
SFR	550°C	530°C	43
MSR	700-800°C	680-780°C	49-52
SCWR	510-550°C	500°C	42
VHTR	1000°C	800°C[2]	53

Notes:

1. Nuclear News, Nov. 2002
2. Limited by corrosion, and to a lesser extent by dissociation
3. IHX ΔT is 50°C for Gas/Gas, 20°C for Liquid/ Gas
4. For net plant efficiency subtract approx. 4% for Gas/Gas house loads and 2% for Liquid/Gas combinations

As noted earlier (in Section 1.2), in the 1970's the combination of S-CO_2 cycles with sodium cooled fast reactors was evaluated in Germany for a turbine inlet temperature of 520°C. (P-1)(M-2) Efficiencies of 37.7 to 42.7% were estimated in one study, and as low as 36.5% (34.85% net) in another, compared to 41% for a Rankine cycle. It was concluded that the lower S-CO_2 efficiency could not be offset by capital savings.

Thus, while re-examination may be in order, to take credit for S-CO_2 PCU modularization, this should be given a lower priority. It does not appear, for example that one can eliminate the intermediate loop because of the spontaneous reaction (negative ΔG):

` $$CO_2 + 2Na \rightarrow Na_2O + CO$$

Hence, a major capital savings is unlikely. Lead, however, is not susceptible to a similar reaction, and an initial cursory check suggests that molten salt constituents such as ZrF_4 should also be unreactive.

In other words, the following reactions have a positive ΔG:

$$2CO_2 + ZrF_4 \rightarrow ZrO_2 + 2CO\ F_2$$
$$2CO_2 + UF_4 \rightarrow UO_2 + 2CO\ F_2$$
$$CO_2 + Pb \rightarrow PbO + CO$$
$$2CO_2 + Pb \rightarrow PbCO_3 + CO$$

However, the ΔG values were checked at 25°C. Checks at higher temperature and for other possible reactions are required before absolute immunity can be claimed. Of course, simple autoclave experiments should also be carried out to confirm stability.

The GFR and VHTR could both benefit, as already discussed in section 3.4 for the very similar MHTGR example. One additional area worth investigation is the use of S-CO_2 as a bottoming cycle for plants designed to produce hydrogen using thermochemical processes, since the latter require 800-1000°C. Similar synergism may result for units designed to produce H_2 by high temperature electrolysis of steam (HTES).

The most promising application may well be with MSR units designed for either thermochemical or HTES H_2 production and/or electricity generation. This is because molten salt is a much better heat transfer medium than gas, so that the ΔT across IHX units, and primary pumping power, are both reduced. The S-CO_2 cycle has the significant advantage of a high CO_2 return temperature (only about 150°C lower than the turbine inlet temperature), which helps avoid the problem of freezing the molten salt.

A generic temperature upper limit on indirect cycle CO_2 applications is set by its dissociation:

$$2CO_2 \leftrightarrows 2CO + O_2$$

For pure gases and CO_2 at 20 MPa Chang Oh calculates that the equilibrium ratio of the partial pressure of O_2 to that of CO_2 is 10^{-6} at 950°C (O-1).

Hence material corrosion and high temperature creep are more likely to be practical limitations. In thermal reactors the reaction of CO_2 with graphite limits the gas temperature to about 650°C (as in the AGR units in the UK). Furthermore in direct cycle applications the issue of CO_2 radiolysis must be addressed.

3.5 Recent Relevant Information

Reference (D-5), just published, summarizes germane work done at MIT under other auspices to consistently evaluate power cycle selection for lead-alloy-cooled fast reactors rated at 700 MWth: about that needed to power a 300 MWe PCU. Table 3.3 shows some of the findings relative to present concerns. As can be seen, S-CO_2 is credited with a higher efficiency than steam; and helium, at the modest temperatures tolerable, is a non-contender. Also noteworthy is the difference between gross and net efficiency. We find that many publications do not clearly distinguish which is being reported, leading to unnecessary confusion.

The above reference also notes that the balance of plant (BOP) accounts for about 40% of the total capital cost, but offers no quantitative estimates of the S-CO_2 capital cost savings. The non-reactor-plant part of total direct costs is 43% in the GCRA MHTGR-GT-IC cost estimate. Hence 40% appears to be a useful reference point for projecting the impact of savings.

Table 3.3 Characteristics of Indirect Power Cycles for a Pb Alloy Cooled Reactor

Parameter	Cycle			
	Superheated Steam	Supercritical Steam	He	S-CO_2
Turbine inlet T, °C	544	546	543	530
Gross efficiency, %	42.7	44.6	34.7	44.0
Net efficiency, %	39.7	41.5	33.1	42.2
Net MWe	278	290	231	296

A companion publication (H-1) opines that the S-CO_2 BOP plant cost could be as small as 25% to 50% of the GE ALMR (sodium cooled LMR) Rankine cycle BOP value, and correspondingly estimates that the total plant capital cost would be reduced by a factor of 0.77 to 0.85 if one used S-CO_2 in place of steam. This corresponds to the BOP being about 30% of total plant cost. This is lower than the 40% previously cited, but may reflect inclusion of some non-direct and owner's costs. Saving 15 to 23% of capital costs which are 63% of the busbar cost would (at the same efficiency) reduce mills/kWhre by 9.5 to 14.5%. Combined with our earlier estimates in section 3.3, this suggests a savings of on the order of 10% may be realizable.

3.6 Relevance of Direct Gas Turbine Cycles

Most current gas reactor studies, both thermal and fast, are for direct cycle applications: e.g. the GA GT-MHR, ESKOM PBMR and the ANL/CEA-led GFR INERI; the MIT MPBR is the exception.

Thus, given that plant efficiency is the dominant factor in determination of the busbar cost of electricity, it is useful to be able to characterize the effect on efficiency of "converting" a direct cycle (DC) unit into an indirect cycle (IC) unit.

Adding an intermediate loop between the core and power cycle reduces cycle efficiency through two effects: blower power consumption and reduced turbine inlet temperature. Approximate relations for these losses (derivable for ideal gas—ideally recuperated Brayton cycles) are:

$$\Delta\eta_w = (1-\eta_o)\frac{\Delta W_b}{Q}$$

$$\Delta\eta_T = (1-\eta_o)\frac{\Delta Th}{Th}$$

where η_o = reference cycle thermodynamic efficiency
ΔW_b = primary circuit blower (circulator) power consumption, MWe
Q = core thermal power, MW_{th}
Th = turbine inlet temperature, °K
ΔTh = reduction in Th due to added IHX heat transfer film drops.

thus if $\eta o = 0.44 \ and \left(W \big/ Q \right) = 0.02, \ \Delta\eta = 1.12\%$

and if $\Delta Th = 40^{\circ}C, \ T_h = 550^{\circ}C = 823^{\circ}K, \ \Delta\eta = 2.72\%$

Another way to look at these penalties is that increasing ΔT_h, hence core outlet and turbine inlet temperatures by 56°C would offset the combined $\Delta\eta$ of 3.84%. Dostal's calculations for the actual <u>non-ideal</u> supercritical CO_2 cycle indicate, however, that the required increase would be closer to 100°C. Thus one is prompted to look into investing in improved IHX units to reduce the penalty.

To offset the added carrying charges due to efficiency loss for a plant having a specific capital cost (I/K) \$/kWe, one can afford to spend an amount:

$$\Delta\left(I \big/ K \right) = \frac{\Delta\eta}{\eta}\left(\frac{I}{K}\right), \ \$ \big/ kWe$$

Thus to avoid a $\Delta\eta$ of 2%, if η = 44% and $\left(I \big/ K \right)$ = 1200 $\$ \big/ kWe$, one can spend 54.5 $\$ \big/ kWe$ or 24 $\$ \big/ kWth$

Hence for the MIT reference 300 MWe S- CO_2 unit, up to 14.4 million dollars <u>extra</u> could be spent on the IHX: several times our preliminary estimates for the cost of size-minimized units.

Although there are no actual "direct" cycles for liquid-cooled GEN-IV reactors, the above relations can be used to evaluate the unavoidable losses incurred by their inherently indirect nature. For example, these relations correctly predict the total 1.43% loss for an intermediate loop employing lead-bismuth eutectic (LBE) as the coolant, and that only about one quarter is due to pumping power consumption. Losses of this magnitude appear quite tolerable: they can be offset by increasing core exit temperatures by approximately 20ºC.

4 Capital Cost Evaluation

4.1 Chapter Introduction

In the preceding chapter a framework was established for making economic comparisons by differential modification of existing studies carried out by industrial groups having architect-engineer (AE) input: for examples Refs (G-1) and (B-1). The dominant importance of the thermodynamic efficiency of the power cycle and its capital cost were shown. Values for input parameters were inferred from prior work at MIT and elsewhere, and the net economic advantage of the indirect supercritical CO_2 cycle estimated compared to a Rankine steam cycle. Thanks mainly to the comprehensive evaluations by Dostal and earlier analysts, the estimates of cycle efficiency are on a sound footing. Capital costs, on the other hand, are much more tentative. It is interesting that none of the S-CO_2 cycle studies of the 1950-1980 time frame ventured quantitative cost estimates, but based on engineering judgments, opined that (at competitive thermal efficiency) S-CO_2 cycle compactness and simplicity promised significant cost advantages.

In this chapter, therefore, various aspects of capital cost projections are reviewed. There are two basic approaches commonly used in concert: application of parametric component and whole subsystem scaling correlations of the type long-used by chemical engineers and others, and a specific detailed breakdown of costs according to the (for example) EEDB Code of Accounts developed by DOE/EPRI/AEs for systematization of cost estimates. While a useful start has been made, much of this is still a work in progress.

4.2 Scale-Factor Approach to Preliminary Cost Evaluation

4.2.1 Fundamentals

Table 4.1 shows the effect of pressure relations reported in Ref (S-4) for helium working fluid in a direct cycle. Cost drops significantly with pressure, with the exception of ducting. Overall, the higher pressure of the supercritical CO_2 cycle should result in a significant savings relative to the helium cycle. Moreover, there are additional savings not yet credited to the former due to:

1. Lower temperature (T max of 550˚C vs. 850˚C)
2. High single turboset power rating (300 vs. 50 MWe) attributable to the compact nature of the S- CO_2 turbine and compressors.
3. Single vs. 3 shaft turboset and absence of intercoolers.

Table 4.1 Brayton Cycle Cost Scaling As a Function of Operating Pressure

	Cost Scaling Function	Ratio for 20 MPa / 8 MPa
Recuperator	$P^{-0.55}$ (shell and tube)	**0.60**
Precooler	$P^{-0.35}$ (shell and tube)	**0.73**
Turboset *	$P^{-0.6}$	**0.58**
Ducting	**61 + P (MPa)**	**1.17**

* 1 shaft, 2 compression stages

Reference (S-4) also provides scaling relations which permit estimates of the first two of these factors.

Table 4.2 shows the results. The dominant effect is the power rating attainable in a single turboset. Because both recuperator and precooler operate in the lower range of power cycle temperatures, the savings, if any, are predicted to be small. However if the He were also used in an indirect cycle, the intermediate high temperature heat exchanger cost would be significantly more expensive than that in the cooler S- CO_2 cycle.

Table 4.2 Brayton Cycle Cost Scaling as a Function of Temperature and Power Rating

	Cost Scaling	Cost Ratio
Recuperator	**approx. 10% per 300˚C**	**~1**
Precooler	**~ constant with temperature**	**~1**
Turboset *		
inlet T:	$3.35 + \left(\frac{T_{\circ C}}{1000}\right)^{7.8}$	**0.93 (650 vs. 850)**
power rating: **<u>per Mwe</u>**	$W^{-0.32}$	**0.56 (300 vs. 50 MWe)**
Ducting	$57 + \left(\frac{T_{\circ C}}{100}\right)^{2}$	**0.77 (650 vs. 850)**

* 1 shaft, 2 compression stages

It is important to note that the scaling relations developed by Schlenker were for a helium cycle. Nevertheless most trends should also hold for CO_2 working fluid. One major issue relevant to intercomparison between He and CO_2 is the much higher recuperator duty called for in the latter: about 2.5 times the MWth per MWe compared to the He cycle. However, in actual optimized cycles (CO_2 at 20 MPa, He at 7 MPa) the recuperator volumes, hence costs, are approximately equal.

These values encouraged our assumption in Chapter 3 of an approximate composite savings of 20% for S-CO_2 power cycle capital costs.

4.2.2 The Effect of Temperature on Cost

The Brayton Cycle recuperator and the reactor-to-power cycle intermediate heat exchanger (IHX) are large expensive components. Heatric™ representatives recommend using 30 $/kg for steel units. For our nominal 300 MWe unit, then, the S-CO_2 recuperator (which has a thermal duty 2.5 times that of the reactor core) would cost about $16/KWe. The IHX would then be $6.4/KWe provided the steel (Type 347) can withstand the higher temperature service. If, for example (as in a He-cooled counterpart) Incoloy-800 at 1000°C had to be used, an increase in cost by a factor of seven is projected in Ref (W-1).

Reference (P-2) also provides relative cost factors for heat exchangers constructed of various materials, as follows:

Table 4.3 Material Cost Factors

Material		Cost Multiplier
Carbon	Steel	1.0
304 L	SS	1.8
316 L	SS	2.2*
Ti		2.8
Incoloy	825	3.0
Inconel	625	5.0
Hastelloy	C-276	5.9
Zirconium		7.7

*selected by ANL for general service in S-CO_2 ; hence also our base-case material

4.4 Heat Exchanger Costs

One of the key enabling technologies which have motivated revival of the S-CO_2 as a serious contender for advanced reactor service is the extremely compact printed circuit heat exchanger (PCHE) of the type manufactured since the early 1990's by Heatric™. They are currently specified for use as the intermediate heat exchanger, recuperators and the precooler in the power cycle. Hence their cost is an important aspect of total S-CO_2 plant costs.

Heatric™ representatives have recommended we use 30$/kg (based on total component weight) as the cost of a standard stainless steel PCHE (this is the actual billing practice they employ with their largest customers in the North Sea offshore oil business).

Based on a heat exchanger core thermal loading of 40 MW/m^3, a volume average core density of 4000 kg/m^3 and a total/core weight ratio of 1.5, a 680 MWth IHX (for a 300 MWe PCU @44% efficiency) would cost approximately 3 x 10^6\$, and the recuperators (@2.5/1 recuperated/source energy ratio) 7.5 x 10^6\$, while the 380 MW precooler will cost about 1.7 x 10^6\$, for a total of 12.2 x 10^6\$. This would represent about 3% of a total unit capital cost of 1400$/kWe for a 300 MWe reactor. The above values are in good agreement with Gezelius' estimates of 1.4 to 4.1 x 10^6\$ for an IHX (G-2). For high temperature service the IHX cost could easily be 2 or 3 times higher. Thus these costs are modest, but significant in that other compact designs, and certainly conventional shell and tube units, are more expensive. Since Heatric™ designs would be unsuitable as a Rankine cycle steam generator, this savings favors the S-CO_2 cycle.

Another point worth noting is that only in the past two years, Heatric™ has developed an improved design designated MP (for multiported) , which provides true counterflow (as opposed to the Z-flow in their earlier designs). This permits a further reduction in size/weight/cost/pressure drop—up to 50% according to Heatric™. We have not yet fully taken into account these further savings. For example, all of Dostal's system performance and cost estimates are based on Z-flow, straight-channel units. Further progress is impeded by the fact that Heatric™'s current product employs "wavy" or "zigzag" channels, which reduce core size by a factor of about 2 to 3, for which literature heat transfer and pressure drop correlations are inadequate for independent verification of design performance (G-2).

Thus we expect to achieve further modest cost reductions as our independent capability to model PCHE units is enhanced. It appears that the most productive approach will be to increase IHX size so as to reduce the log mean ΔT between the countercurrent streams. Values as low as 10°C should be realizable, which for fixed primary coolant core outlet temperature, will allow increasing turbine inlet temperature, hence cycle efficiency. Applying the methods in Chapter 3 leads to a reduction in busbar cost of about 5% for a gas-to-gas indirect cycle.

5 Concluding Discussion and Planning

5.1 General Observations

Comparison of S-CO_2 to steam cycles involves projection of future capabilities for both cycles. The current fossil maximum supercritical steam commercial offering is 625°C (MHI). The US DOE VISION-2020 fossil program is aiming at 750°C. Dostal has defined three categories of S-CO_2 cycle designs: "basic" at 550°C, "advanced" at 650°C and "high performance" at 700 °C. Since CO_2 is less corrosive to steels than steam at the same pressure and temperature, it is likely that S-CO_2 could match H_2O applications in this regard. However CO_2 will ultimately come up against another limit—dissociation. In the absence of radiolysis and the presence of susceptible materials such as graphite, a practical limit of at least 800°C and perhaps even 950°C should be tolerable. One should recall that conventional CCGT fossil-fired gas turbine blades endure a mixture of CO_2, H_2O and N_2 at about 1250°C (K-4). Thus we cannot choose between these alternatives based mainly on working fluid maximum usable temperature.

Dostal has compared S-CO_2 and steam cycle efficiencies: see Fig. 5.1. Above about 550°C, S-CO_2 realizes an efficiency advantage which increases with temperature (using a plausible extrapolation for steam). Since S-CO_2 has a lower capital cost, above 550°C we can predict a growing cost-of-energy advantage. Thus our final economic assessment will hinge on what turbine inlet temperature is assumed. This in turn depends on the primary system (and IHX) capabilities, hence the type of reactor specified. Accordingly, savings are very application dependent.

The above considerations suggest that we focus on a limited number of specific applications in our future work. Since the VHTR has top priority in the US programs, and likewise for similar HTGRs worldwide, this would appear to be a natural venue. It is also a natural extension of our work using the GCRA study of Rankine vs. He Brayton in Chapter 3.

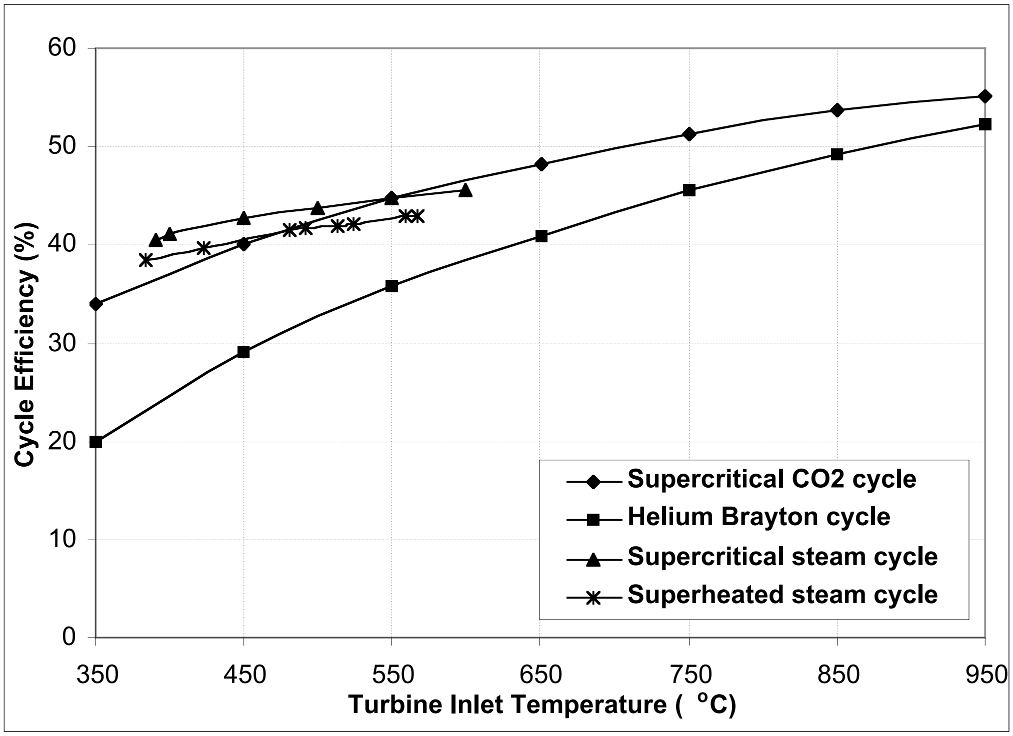


Fig. 5.1 Cycle Efficiency comparison of Advanced Power Cycles

5.2 Additional Perspectives on Cost Reduction

GCRA estimated that reactor plant equipment for their MHTGR GT/IC unit would account for 56% of total direct costs (TDC). Hence if we define balance-of-plant (BOP) as everything else, BOP accounts for 44%. Their (helium indirect) turbine plant equipment (part of BOP) only amounted to 15% of TDC. Hence substituting even a much cheaper S-CO_2 power conversion unit might only reduce TDC by on the order of 5%. Thus we must also look into non-turbine BOP costs, 29% of TDC, for additional savings.

If one instead uses their Rankine steam cycle unit as the base case, reactor plant equipment was 50% of TDC, hence BOP is also 50%, while steam turbine plant equipment was 18% of BOP. Hence, using this as the base case will not alter the situation significantly as regards capital cost savings. However, as we have noted in Chapter 3, the efficiency advantage compared to the steam cycle's 38.5% would lead to significant busbar-cost-of-electricity savings.

If one re-optimizes the entire plant design, then the ability of S-CO_2 to match helium cycle efficiency at a turbine inlet temperature which is about 150°C lower should yield significant additional savings.

It is such considerations which led us, in the abstract, to conservatively project an overall savings of about 10% compared to other <u>indirect</u> cycles. For a <u>direct</u> S-CO_2 cycle vs. an <u>indirect</u> S-CO_2 cycle, we would expect to meet or beat the additional 18% improvement estimated by GCRA in their helium Brayton cycle comparisons.

Table 5.1 summarizes the status of the cost of energy projections carried out to date. As is evident, assurance of high plant efficiency remains an important turbomachinery and heat exchanger design goal. Also obvious is the need to better understand why the GCRA study predicted that their helium turbine Brayton Cycle power plant was more expensive than their steam cycle base case. Everyone who has looked into the S-CO_2 cycle in the past has expressed the opinion that it, at least, should be cheaper than the steam cycle.

Table 5.1 Summary of Cost Assessment to Date

1. Likely Savings vs. Rankine Cycle MHTGR

1.1 Due to Efficiency*

T°C	Net η, %	$\Delta\eta$, %	$-\frac{\Delta\eta}{\eta} = \frac{\Delta e_b}{e_b}$, %
550	38.5	0	0
600	40.7	2.2	-5.7
650	42.8	4.3	-11.2
700	44.5	6.0	-15.5
750	46.0	7.5	-19.5
800	47.0	8.5	-22.1

*vs. Rankine Cycle MHTGR @ η=38.5%, core T_{OUT} = 850°C

1.2 Due to Turbine Plant Cost Reductions

ΔI/I, %	$\Delta e_b/e_b$, %
+ 10%* added cost	+6
0	0
-10	-6
-20	-12

*Same increase as MHTGR He IC vs. Rankine

2. Some Speculative Additional Savings

		$\Delta e_b/e_b$, %
2.1	Shorter Construction (2 mo in 50)	0.9
2.2	Smaller Heat Sink (by 10%)	0.1
2.3	Smaller BOP Structures, Simpler Aux Systems (by 20%)	1.0
2.4	Reduce Primary System Temperature (By ≥150°C)	2.0
2.5	Reduce O&M (By 20%)	3.5

Nevertheless, on the other side of the ledger it is highly unlikely that adoption of the indirect S-CO_2 cycle, by itself, could reduce nuclear-generated electricity costs by the (very roughly) 30% needed to make nuclear competitive with coal and combined cycle gas units, as projected in the recent studies reported in Refs (M-1) and (C-1).

5.3 Planning

Table 5.2 summarizes our planned agenda for further cost studies. So far we have focused attention on the two most important of the 2-digit EEDB account categories; in the future we should dig more deeply into all 51 3-digit accounts (35 direct, 16 indirect). Note that so far we have assumed that indirect costs (about 27% of total, or 1.37 times direct for the MHTGR IC target plant) scale up or down directly proportional to direct costs. This proposition is worth further scrutiny.

Also shown in the table are some further power cycle design tradeoff studies, which could increase thermal efficiency (MWe/MW_{th})—arguably the single most important determinant of busbar cost.

Table 5.2 Framework for Cost Assessment

Effects Evaluated to Date	
(a)	Higher cycle efficiency
(b)	Power conversion cycle capital costs
Additional Contributors for Inclusion or Refinement	
(1)	Shorter construction time due to modularity, simplicity; hence reduced interest during construction
(2)	Examine the 27% of total costs which are indirect costs
(3)	Account for reduced heat sink size, effect on electrical plant
(4)	Reduced building sizes: power conversion cycle and auxiliary buildings
(5)	Simplified gas storage and purification systems
(6)	Simplified component cooling systems
(7)	Credit for use of conventional H_2 cooled generator, other off-the shelf CCGT electrical components
(8)	Reduce O&M costs due to increased BOP reliability; shorter maintenance outages
(9)	Credit for materials savings where temperature is reduced
Model Refinement and Tradeoff Studies	
(A)	Improve turbomachinery modeling; increase cycle efficiency
(B)	Eschew inventory control, compare savings to reduced part-load efficiency
(C)	Oversize the IHX to reduce log mean ΔT loss, increase PCU efficiency
(D)	Re-optimize reactor core to reduce its ΔP and hence circulator rating and power consumption
(E)	Re-evaluate one and two stages of reheat
(F)	Optimize S-CO_2 turbine inlet temperature for VHTR and MSR primary reactor systems

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